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On the Generation of 3 Meter Irregularities During Equatorial Spread F by Low Frequency Drift Waves

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We consider the linear theory of low frequency drift waves for parameters typical of the ionosphere during equatorial Spread F. These waves are considered to be generated by density gradients associated with long wavelength primary plasma fluid instabilities (e.g., collisional Rayleigh-Taylor). We include electron-ion, electron-neutral and ion-ion collisions in our analysis. We find that a collisional drift wave can occur in the 3 meter regime but that it is heavily damped by ion viscosity. For density gradient scale lengths $\gtrsim$ 75m, it is required that $n < 2 \times 10^3$ cm^{-3} for wave excitation to occur.

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CONTENTS

I. Introduction

There has been considerable interest over the recent observations of small-scale irregularities during equatorial Spread F (Farley et al., 1970; Woodman and LaHoz, 1976; Costa and Kelley, 1978a,b; Huba et al., 1978). Radar backscatter measurements indicate density fluctuations with scale sizes of 3m, 1m and 36cm. Moreover, since density inhomogeneities exist with scale lengths as short as 30m (Costa and Kelley, 1978a) (these scale lengths presumably arise because of the primary growth of long wavelength fluid modes, e.g., the collisional Rayleigh-Taylor instability), it is plausible to consider whether or not the excitation of drift waves could be responsible for the small-scale irregularities. Recently, Huba et al. (1978) have demonstrated that the ion-drift-cyclotron and the lower-hybrid-drift instabilities are viable candidates to produce the 1m and 36cm irregularities. However, the 3m irregularities cannot be explained by these instabilities based on linear theory. Costa and Kelley (1978a,b) have suggested the universal drift instability (collisionless, low-frequency drift instability) may account for the 3m irregularities. Unfortunately, their assumption of a collisionless plasma is questionable for typical ionospheric parameters and their theory is limited to wavelengths greater than 6m.

In this brief report we consider the linear theory of low frequency drift waves for parameters typical of the ionosphere during equatorial Spread F. We use kinetic theory to describe the ion and electron dynamics. (Note: A kinetic theory is required for the ions

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since for the 3m irregularities $k_\perp r_{Li} \approx 10 >> 1$, where r_{Li} is the mean ion Larmor radius). Electron-ion and electron-neutral collisions are considered using the Bhatnagar-Gross-Krook (BGK) collision model (Bhatnagar et al., 1954). We also include ion-ion collisions via a model Fokker-Planck equation for the numerical results (Dougherty, 1964; Huba and Ossakow, 1979) and the Landau collision integral for the analytic results (Rukhadze and Silin, 1969; Mikhailovskii, 1974). We find that a collisional drift wave can occur in the 3m regime but that it is damped by ion viscosity unless $n < 2 \times 10^3$ cm^{-3} for density gradient scale lengths $\gtrsim$ 75m. Thus, it is improbable that low frequency drift waves can linearly generate the 3m irregularities observed during equatorial Spread F.

The structure of the paper is as follows. In the next section we present the basic assumptions and the dispersion equation considered in the analysis. Section III contains the analytical and numerical results of our theory. In the final section we discuss the implications of our results concerning the 3m irregularities.

II. Basic Assumptions and the Dispersion Equation

The geometry we consider is described as follows. The ambient magnetic field is $\underset{\sim}{B} = B_o \hat{e}_z$, the density depends only on the x coordinate ($n = n_o(x)$) and the temperature is assumed to be constant. Each species α(electrons and 0^+ ions) has a drift velocity $\underset{\sim}{V}_\alpha = V_{d\alpha}\,\hat{e}_y$ where $V_{d\alpha} = (v_\alpha^2/2\Omega_\alpha)\; d\,\ell n/dx$ is the diamagnetic drift velocity, $v_\alpha = (2T_\alpha/m_\alpha)^{1/2}$ is the thermal velocity, $\Omega_\alpha = e_\alpha B_o/m_\alpha c$ is the cyclotron frequency and $n = n_e \approx n_i$. A net current exists in the plasma

$\underset{\sim}{J}_o = en(V_{di} - V_{de})\hat{e}_y = enV_{di}(1 + T_e/T_i)\hat{e}_y$ which provides the free energy to drive an instability. Perturbed quantities vary as $\exp\ i(k_\perp y + k_\parallel z - \omega t)$ and we consider only electrostatic oscillations. We make use of the local approximation which requires $kL_n >> 1$ where $L_n = (d\ \ell n\ n/dx)^{-1}$ is the density gradient scale length. We include electron-ion and electron-neutral collisions ($\nu_e = \nu_{ei} + \nu_{en}$) and ion-ion collisions ($\nu_i = \nu_{ii}$). We neglect ion-neutral collisions by requiring $\nu_{in} << k_\parallel v_i$ which restricts the results of the analysis to altitudes above 300 km. Finally, we consider $\omega << \Omega_i, \Omega_e$, $k^2 r_{Li}^{\ 2} >> 1$ $k^2 r_{Le}^{\ 2} << 1$ and $\nu_{ii} << \Omega_i$.

The dispersion equation is found to take the following form within the context of our model

$$D(\omega,k) = 1 + \chi_e + \chi_i = 0 \tag{1}$$

where (Kadomtsev, 1965)

$$\chi_e = \frac{2\omega_{pe}^{\ 2}}{k^2 v_e^{\ 2}} \left[1 + \frac{\omega - k_\perp V_{de}}{k_\parallel v_e} Z(\xi_e) \left\{1 + \frac{i\nu_e}{k_\parallel v_e} Z(\xi_e)\right\}^{-1}\right] \tag{2}$$

and (Huba and Ossakow, 1979)

$$\chi_i = \frac{2\omega_{pi}^{\ 2}}{k^2 v_i^{\ 2}} \left[1 + i\frac{\omega - k_\perp V_{di}}{\Omega_i} \int_0^\infty d\tau\ \exp\left(i\frac{\omega}{\Omega_i}\tau - \Phi_i(\tau)\right)\right]. \tag{3}$$

Here,

$$\Phi_i(\tau) = b_i\left[\cos\theta + \tilde{\nu}_i\tau - e^{-\tilde{\nu}_i\tau}\cos(\tau-\theta)\right] + \frac{k_\parallel^{\ 2}}{k_\perp^{\ 2}}\frac{b_i}{\tilde{\nu}_i^{\ 2}}\left[\tilde{\nu}_i\tau - 1 + e^{-\tilde{\nu}_i\tau}\right] +$$

$$+ i\frac{k_\perp V_{di}}{\Omega_i}\left[e^{-\tilde{\nu}_i\tau}\sin\tau + \tilde{\nu}_i(1 - e^{-\tilde{\nu}_i\tau}\cos\tau)\right],$$

$\xi_e = (\omega + i\nu_e)/k_{\|}v_e$, $\omega_{p\alpha}^2 = 4\pi ne^2/m_\alpha$, $\tilde{\nu}_i = \nu_{ii}/\Omega_i$, $\theta = 2\tan^{-1}\tilde{\nu}_i$ and $b_i = \frac{1}{2}k_\perp^2 r_{Li}^2$. Several comments are in order concerning the validity of this dispersion equation. Equation (2) is based on the BGK collision model and, strictly speaking, only describes electron-neutral collisions. However, this model reproduces the results based on fluid theory in the collisional regime and the kinetic results in the collisionless regime. Here we define collisional (collisionless) as $\nu_e \gg k_{\|} v_e (\nu_e \ll k_{\|}v_e)$. Thus, only in the semi-collisional regime $(\nu_e \approx k_{\|}v_e)$ is Eq. (2) suspect and this regime is not relevant for the ionospheric parameters of interest. Equation (3) is based upon a model Fokker-Planck equation (Dougherty, 1964) and is valid only for $\nu_{ii} \ll \Omega_i$ and $k_\perp^2 r_{Li}^2 \gg 1$ which is precisely the regime of interest. The numerical results presented in the next section will be based on Eqs. (1)-(3).

Although Eq. (3) does not lend itself to a simpler analytical expression for the parameters we are concerned with, an alternative formulation of χ_i based upon the Landau collisional integral (Rudkadze and Silin, 1969) permits analytic solutions to Eq. (1) in several limits. In particular, for $k_\perp^2 r_{Li}^2 \gg 1$, $\omega \gg k_{\|}v_i$ and $\nu_{ii}k_\perp^2 r_{Li}^2 \ll \omega$ one can show that (Mikhailovskii, 1974)

$$\chi_i = \frac{2\omega_{pi}^2}{k^2 v_i^2}\left[1 - \left(1 - \frac{k_\perp V_{di}}{\omega}\right)\frac{1}{\sqrt{\pi}}\,\frac{1}{k_\perp r_{Li}}\left(1 - i\,\frac{3(\pi+1)}{4\sqrt{2}}\,\frac{\nu_{ii}}{\omega}k_\perp^2 r_{Li}^2\right)\right]. \quad (4)$$

We will use this expression in the following section to derive simple expressions for the eigenfrequency, $\omega = \omega_r + i\gamma$.

III. Theoretical Analysis

A. Analytical results.

We now present several analytical results for a variety of conditions to elucidate the physical nature of the instability and the effects of collisions. For all the cases considered we will assume that $k_\perp^2 r_{Li}^2 \gg 1$, $k_\parallel v_e \gg \omega \gg k_\parallel v_i$, $\omega \ll k_\perp V_{de}$, $T_e = T_i$, $k_\perp^2 r_{Le}^2 \ll 1$, $\omega \ll \Omega_i$, Ω_e and $\gamma \ll \omega_r$.

1. $\nu_{ii} = 0$ and $\nu_e = 0$

In the collisionless limit the dispersion equation becomes

$$D(\omega,k) = 2 - \frac{k_\perp V_{de}}{\omega} \frac{1}{\sqrt{\pi}} \frac{1}{k_\perp r_{Li}} - i\sqrt{\pi}\frac{k_\perp V_{de}}{k_\parallel v_e} = 0 \tag{5}$$

which yields the solution

$$\omega_r = \frac{k_\perp V_{de}}{2\sqrt{\pi}\, k_\perp r_{Li}} \; ; \; \gamma = \frac{k_\perp^2 V_{de}^2}{2 k_\parallel v_e} \frac{1}{k_\perp r_{Li}} . \qquad 6)$$

We comment that the instability is kinetic and is excited through an electron-wave resonance. Relaxing the restriction $\gamma \ll \omega_r$, it is found that (Mikhailovskii, 1974)

$$\gamma_M \approx \omega_r \approx \frac{1}{8\sqrt{\pi}} \frac{v_i}{L_n} \tag{7}$$

for $k_\parallel \approx \frac{\sqrt{\pi}}{2} \frac{k_\perp V_{de}}{v_e}$ where γ_M denotes the maximum growth rate. It is interesting to note that in the limit $k_\perp^2 r_{Li}^2 \gg 1$, γ_M is independent of wavenumber.

2. $\nu_{ii} \neq 0$ and $\nu_e = 0$

In this limit, in which we neglect electron collisions but include ion-ion collisions, the dispersion equation becomes

$$D(\omega,k) = 2 - \frac{k_\perp V_{de}}{\omega} \frac{1}{\sqrt{\pi}} \frac{1}{k_\perp r_{Li}} \left(1 - i \frac{3(\pi+1)}{4\sqrt{2}} \frac{\nu_{ii}}{\omega} k_\perp^2 r_{Li}^2\right)$$

$$- i \sqrt{\pi} \frac{k_\perp V_{de}}{k_\| v_e} = 0 \tag{8}$$

where we have assumed $\nu_{ii} k_\perp^2 r_{Li}^2 << \omega$. Solving Eq. (8) yields

$$\omega_r = \frac{k_\perp V_{de}}{2\sqrt{\pi} k_\perp r_{Li}} \; ; \; \gamma = \frac{k_\perp^2 V_{de}^2}{2k_\| v_e} \frac{1}{k_\perp r_{Li}} - \frac{3(\pi+1)}{4\sqrt{2}} \nu_{ii} k_\perp^2 r_{Li}^2 . \tag{9}$$

Again, the instability is kinetic but ion viscosity provides a damping mechanism which is particularly effective at the shorter wavelengths.

3. $\nu_{ii} \neq 0$ and $\nu_e \neq 0$

We finally consider the fully collisional limit and assume $\nu_{ii} k_\perp^2 r_{Li}^2 << \omega$, $\omega << \nu_e$, $\nu_e >> k_\| v_e$ and $\nu_e \omega < k_\|^2 v_e^2$. The dispersion equation is

$$D(\omega,k) = 2 - \frac{k_\perp V_{de}}{\omega} \frac{1}{\sqrt{\pi}} \frac{1}{k_\perp r_{Li}} \left(1 - i \frac{3(\pi+1)}{4\sqrt{2}} \frac{\nu_{ii}}{\omega} k_\perp^2 r_{Li}^2\right)$$

$$- 2i \frac{\nu_e k_\perp V_{de}}{k_\|^2 v_e^2} \tag{10}$$

for which

$$\omega_r = \frac{k_\perp V_{de}}{2\sqrt{\pi} k_\perp r_{Li}} \; ; \; \gamma = \frac{\omega_r \nu_e k_\perp V_{de}}{4k_\|^2 v_e^2} - \frac{3(\pi+1)}{4\sqrt{2}} \nu_{ii} k_\perp^2 r_{Li}^2 . \tag{11}$$

In this limit the nature of the instability has changed from being a kinetic (collisionless) instability to a collisional instability. However, ion viscosity is still an effective damping mechanism. For parameters typical of the ionosphere this final limit is the most relevant. It should be noted that many of the approximations made which led to the simplified dispersion equations breakdown for realistic values of ν_{ii}, ν_e and L_n and a numerical analysis is required to determine ω.

B. Numerical results.

We now present the results of a numerical analysis based upon Eqs. (1)-(3). The parameters chosen which are common to both Figs. (1) and (2) are: $T_e/T_i = 1.0$, $\omega_{pe}/\Omega_e = 10.0$ and $V_{di}/v_i = 0.04$ which corresponds to a density gradient scale length $L_n \approx 75\text{m}$ for a 1000°K 0^+ plasma in a 0.3 Gauss field. We mention the results are relatively insensitive to the parameter ω_{pe}/Ω_e.

In Fig. 1 we present the growth rate spectrum γ/Ω_i vs. $k_\perp r_{Li}$ for different collisional conditions. The solid curve (—) represents the collisionless case ($\nu_{ii} = 0$ and $\nu_e = 0$), the dashed curve (----) represents only electron collisions ($\nu_{ii} = 0$ and $\nu_e/\Omega_i = 2.0$), the dotted curve (.....) represents only ion-ion collisions ($\nu_{ii}/\Omega_i = 1.0 \times 10^{-5}$ and $\nu_e = 0$) and the dash-dot curve (-·-·-·) is fully collisional ($\nu_{ii}/\Omega_i = 1.0 \times 10^{-5}$ and $\nu_e/\Omega_i = 2.0$). The value of $k_\parallel/k_\perp$ is chosen to give maximum growth for each value of $k_\perp r_{Li}$. Also, as mentioned earlier, Eq. (3) is only valid for $k_\perp^2 r_{Li}^2 >> 1$ when $\nu_{ii} \neq 0$ and has been used for $k_\perp r_{Li} > 4.0$. For $k_\perp r_{Li} < 4.0$ the role of ion viscosity

becomes negligible and the spectra resemble the $\nu_{ii}=0$ spectra in this region. Several points of interest concerning these curves are the following. First, maximum growth for the collisionless case occurs for $k_\perp r_{Li} \approx 0.8$ which is in agreement with the results of Gary and Sanderson (1978). We mention that Costa and Kelley (1978b) incorrectly found maximum growth for $k_\perp r_{Li} \approx 1.5$. Electron collisions cause the peak growth to shift to higher k ($k_\perp r_{Li} \approx 1.0$) while ion-ion collisions do not affect the wavenumber of maximum growth. Second, for $k_\perp r_{Li} > 4$ the growth rate is relatively constant for a large range of $k_\perp r_{Li}$ as anticipated from Eq. (7) for the collisionless case. Third, the electron collisional drift instability has lower growth rates over most of the spectrum (except for $k_\perp^2 r_{Li}^2 << 1$) than the collisionless instability. Finally, ion-ion collisions heavily damp the short wavelength modes and can stabilize the instability.

In Fig. 2 we plot γ_m/Ω_i vs. ν_e/Ω_i for ν_{ii}/Ω_i = 0., 1.0×10^{-5}, 2.0×10^{-5}, 3.0×10^{-5}, 4.0×10^{-5}, 5.0×10^{-5}, and $k_\perp r_{Li} = 10.0$ (which roughly corresponds to 3m wavelengths). Here γ_m denotes the maximum value of the growth rate with respect to $k_\parallel/k_\perp$. The important features of this curve are: (1) electron collisions, although responsible for the instability when $\nu_e/\Omega_i > 0.6$, have a stabilizing influence as ν_e is increased and (2) relatively infrequent ion-ion collisions can stabilize the instability due to ion viscous damping.

IV. Discussion

We have presented an analysis of low frequency drift waves based on kinetic theory including electron (i.e., electron-ion and electron-

neutral) and ion (i.e., ion-ion) collisions. The primary purpose is to determine whether or not drift waves can produce the 3m irregularities observed during equatorial Spread F based on linear theory. We now address this question.

For typical ionospheric parameters it is expected that $\nu_e \approx 200\text{-}1000\ \sec^{-1}$ and $\Omega_i \approx 200\ \sec^{-1}$ so that $\nu_e/\Omega_i \approx 1\text{-}5$. Based on our theory we find that a collisional drift wave can be excited in this parameter range. However, ion viscosity can heavily damp the short wavelength modes ($k_\perp^2 r_{Li}^2 >> 1$) and even infrequent ion-ion collisions can stabilize the instability. From Fig. 2 we see that the 3m mode is stabilized for $\nu_{ii}/\Omega_i > 5 \times 10^{-5}$ when $L_n \approx 75$m and $\nu_e > \Omega_i$. For $T_i = 1000^\circ$K and B = 0.3 Gauss this corresponds to $n > 2 \times 10^3\ \text{cm}^{-3}$ which is generally the situation in the F region. The exception, of course, would be deep inside a plasma depletion (bubble) where plasma densities can fall below this value. Still, this would not explain the 3m backscatter return observed on the bottomside of the F region by Woodman and LaHoz (1976) just after sunset when Spread F begins.

An approximate analytic expression can be derived relating density and density gradient scale length to determine the conditions under which instability can occur. We demand that $\gamma_o > \nu_{ii} k_\perp^2 r_{Li}^2/2$ for instability where

$$\gamma_o = \frac{r_{Li}}{L_n} \frac{1}{8\sqrt{\pi}} \Omega_i \tag{12}$$

is the maximum growth of the collisionless instability in the regime $k_\perp^2 r_{Li}^2 >> 1$ (Eq.(7)). Although the collisionless mode is usually not excited, its growth rate is not significantly different from the

collisional mode. For $T_i = 1000^{o}K$ and $\Omega_i = 200\ sec^{-1}$ we obtain the following condition for instability

$$n < \frac{r_{Li}}{L_n} \frac{1}{k_\perp^2 r_{Li}^2} 2 \times 10^6\ cm^{-3}. \tag{13}$$

Thus, for $k_\perp r_{Li} = 10$ and $L_n/r_{Li} \approx 10$ we require $n < 2 \times 10^3\ cm^{-3}$ for instability which is in good agreement with the numerical estimates.

In conclusion, it seems unlikely that a linear theory of drift waves can account for the observation of 3m irregularities during equatorial Spread F. Although it is possible to generate sharp density gradients ($L_n \approx 10\ r_{Li}$) on the edges of density depletions (bubbles) which are sufficient to excite a collisional drift instability, the condition (Eq. (13)) to overcome ion viscuous damping is difficult. On the other hand, longer wavelength modes ($k_\perp r_{Li} \lesssim 1$) are more readily excited since ion viscuous damping is less effective for these modes. We suggest it may be possible for a large amplitude, long wavelength mode to nonlinearly generate the short wavelength turbulence via a parametric process and we are presently investigating this possibility.

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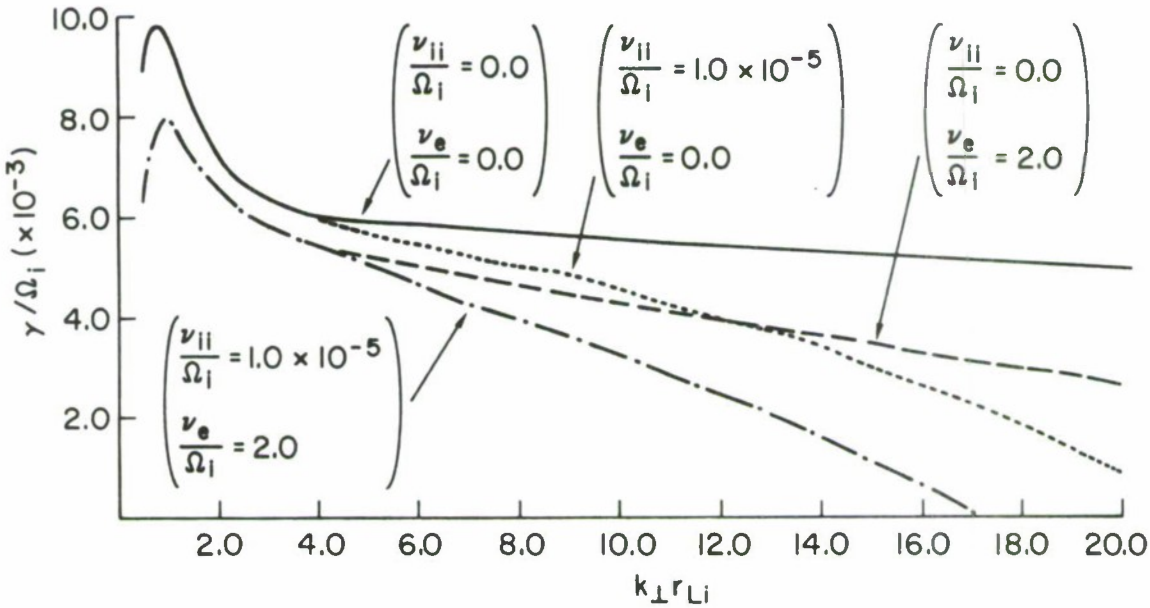

Figure 1. Growth rate spectrum γ/Ω_i vs. $k_\perp r_{Li}$ for $T_e/T_i = 1.0$, $\omega_{pe}/\Omega_e = 10.0$ and $V_{di}/v_i = 0.04$ ($L_n \approx 75$m). The growth rate has been maximized with respect to $k_\parallel$ for each value of $k_\perp r_{Li}$ and typically $k_\parallel/k_\perp \approx 10^{-4} - 10^{-3}$. Here, the collisional parameters are:

(———) $\nu_{ii} = 0$; $\nu_e = 0$

(------) $\nu_{ii} = 0$; $\nu_e = 2.0\ \Omega_i$

(·····) $\nu_{ii} = 1.0 \times 10^{-5}\ \Omega_i$; $\nu_e = 0$

(-·-·-) $\nu_{ii} = 1.0 \times 10^{-5}\ \Omega_i$, $\nu_e = 2.0\ \Omega_i$

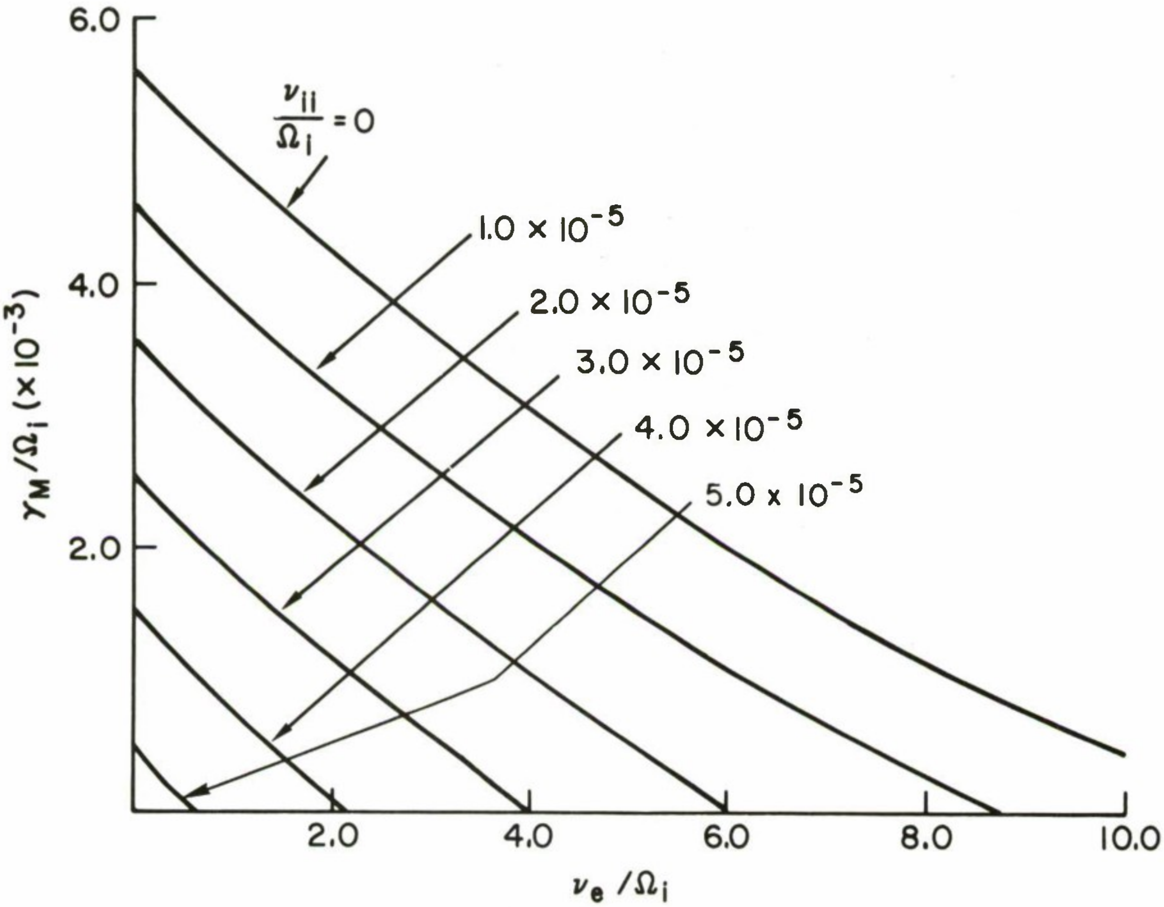

Figure 2. A plot of γ_m/Ω_i vs. ν_e/Ω_i for the same parameters as Fig. 1 with $k_\perp r_{Li} = 10.0$ and $\nu_{ii}/\Omega_i = 0$, 1.0×10^{-5}, 2.0×10^{-5}, 3.0×10^{-5}, 4.0×10^{-5}, 5.0×10^{-5}. Again, γ is maximized with respect to $k_{||}$

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